Augmented Electrothermal Hydrazine Thruster Development

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This paper describes the development of a power-augmented electrothermal hydrazine thruster (AEHT). The operational basis for the development of such devices is briefly presented, and is followed by a summary of appropriate design requirements. The development program is presented by reference to the main areas of investigation and leads logically to the evolution of an integrated unit fully representative of assemblies suitable for flight.

Introduction

THE widespread use of monopropellant hydrazine propulsion systems for satellite attitude and orbit control is directly attributable to their predictable performance, simplicity, and proven reliability. Extensive and continuing development efforts, both in the United States and Europe, have resulted in the availability of a wide range of qualified components and considerable expertise in the design, implementation, and operation of hydrazine systems.

Therefore, it is sensible to retain this fully developed and cost-effective technology for application to the new generation of heavier, high-powered, long-life communication and other application technology satellites. However, the increasing mass and volume of onboard propellant means that performance improvements must be achieved in order to provide a corresponding increase in payload capability.

A unique specific impulse improvement opportunity arises through the utilization of electrical power available from the higher-power satellites. This power could result from excess solar generator power during the early life of the satellite and from power available when the communication payload power demand is low, either on opportunity basis, or on a programmed power-sharing basis. The specific impulse improvement is achievable by increasing the enthalpy of the exothermally reacted monopropellant hydrazine gases by electrical resistive heating within a heat exchanger downstream of the decomposer. The design and development activities of such a power-augmented electrothermal hydrazine thruster are presented in the following sections.

AEHT Description and Design Requirements

The AEHT is based on design requirements shown in Table 1.

One of the main requirements is that the thruster must be compatible with the existing hydrazine propulsion system design of the European Communication Satellite (ECS) with regard to propellant inlet pressure range, thruster interfaces, and off-modulation capabilities.

The environmental requirements such as vibration, acceleration, and shock have not been mentioned in Table 1. However, as the AEHT should be compatible with ECS, the same requirements have to be met: 1) random vibration up to $0.2g^2$/Hz; 2) sinusoidal vibration up to 20g at 35-60 Hz; and 3) 20g linear acceleration in all axes.

Due to these requirements, the AEHT has to be a rugged design not allowing a layout susceptible to vibration. This excludes free-floating heater elements which are not considered anyway as an optimum design from a materials compatibility and reliability point of view.

At the time that development activities were begun, a proven electrothermal hydrazine thruster (EHT) already existed at ERNO. It was decided, therefore, to design the AEHT as a "tandem thruster" consisting of a hydrazine decomposer and a heat exchanger with nozzle.

Figure 1 shows the overall AEHT design concept, which is described below in detail, together with the decomposer design and life test results, the heat exchanger and development, and the AEHT test results.

Decomposer Design and Test Results

Designing an electrothermal hydrazine thruster to function as a decomposer means concentrating on two main areas:

1) The heat exchanger, where the enthalpy increase of the reaction gas has to be achieved in the most efficient way.

2) The decomposer, which can, among others, be one of the life-limiting items of the entire thruster.

Previous development experience with catalytic as well as electrothermal hydrazine thrusters had shown that one of the most important problems to be solved is that of the "nonvolatile residue" (NVR) clogging the injector. However, as two of the catalytic 0.5 N thrusters had already been successfully subjected to more than 100 h of steady-state firing with about 10% reduction of thrust, it was believed that even longer firing durations should be possible.

A problem could arise from the fact that the decomposer had to be designed for a maximum thrust level of about 0.2 N, making a very thin-walled injector tube necessary.

A research and development program resulted in the thruster design presented in Fig. 2. The thruster consists of a thermal barrier with a capillary injector tube and a head end assembly with a single-jet injector. The decomposition chamber contains a thermal capacity consisting of small diameter balls made of platinum/rhodium and a matrix of screens of the same material.

The outer surface of the decomposition chamber is threaded in order to carry redundant sheath heaters.

This thruster was subjected to a life test using monopropellant grade hydrazine. The test was carried out automatically with a duty cycle of 7 min on and 3 min off. The 3 min off time was sufficient for the chamber temperature to return to the starting temperature of about 550°C. In this mode the thruster performed 3140 cycles, giving a total of 358 h of steady-state firing. The thruster operated between 22 and 5.5 bars, and decomposed 84 kg of hydrazine. The final pressure drop amounted to about 8% at 22 bars.

The test results were analyzed, necessary modifications in the injection area implemented, and the final version of the decomposer designed and built. The research and development program had proved that NVR deposition is a function of the injector tube temperature. The NVR deposition can be kept at a sufficiently low level if the injector tube does not

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Table 1 AEHT design requirements

Requirement	Performance
Propellant	Monopropellant grade hydrazine MIL-P-26536C, amendment 1
Inlet pressure range	22-5.5 bars
Inlet temperature range	+4 to +50°C
Nominal thrust	200-50 mN
Specific impulse	≥300 s average
Specific power consumption	1.3 W/mN
Maximum electrical power	300 W
Total operating time	>200 h at 200 mN >800 h at 50 mN
Mission total starts	2000 max
Mission total off-modulations	≥50,000
Mission life	7 yr
Mission total impulse	130,000 Ns/thruster

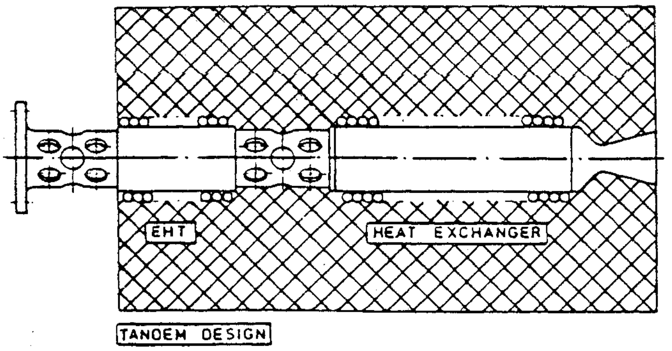

Fig. 1 Overall AEHT design concept.

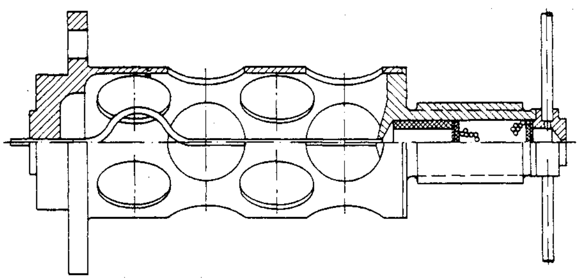

Fig. 2 Decomposer design.

become too hot. This can only be accomplished by painstaking design and the selection of special materials in the injector area. An extensive material-joining program was performed to develop the processes to join refractory metals and high-temperature resistant materials by electron-beam welding and/or high-temperature brazing. Among other processes, brazing with chromium, titanium, platinum, and vanadium were investigated.

The final decomposer design is shown in Fig. 3.

It will be equipped with redundant sheath heaters and two temperature sensors for diagnostic and control purposes. Each of the two heaters has a power consumption of 20 W max at 28 VDC.

The flow control valve is a dual-seat, single-coil design, as used on the flight-proven catalytic 0.5 and 2.0 N thrusters.

The decomposer has been built and assembled to an engineering model of the AEHT heat exchanger.

In this configuration, equipped with heaters, temperature sensors, a chamber pressure transducer, and thermal insulation, the unit has been subjected to a decomposer life test and AEHT verification firing tests.

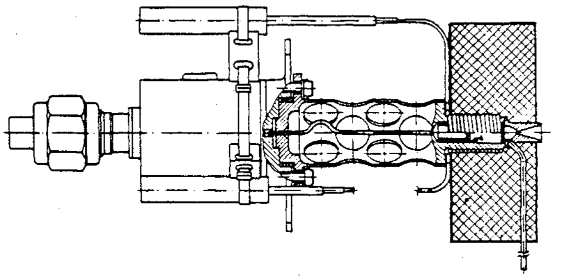

Fig. 3 Final decomposer design.

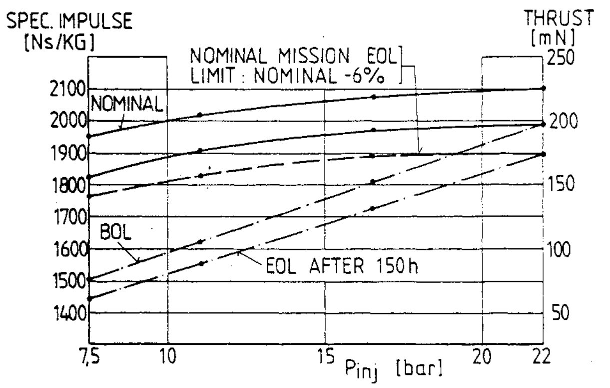

Fig. 4 Decomposer performance characteristics.

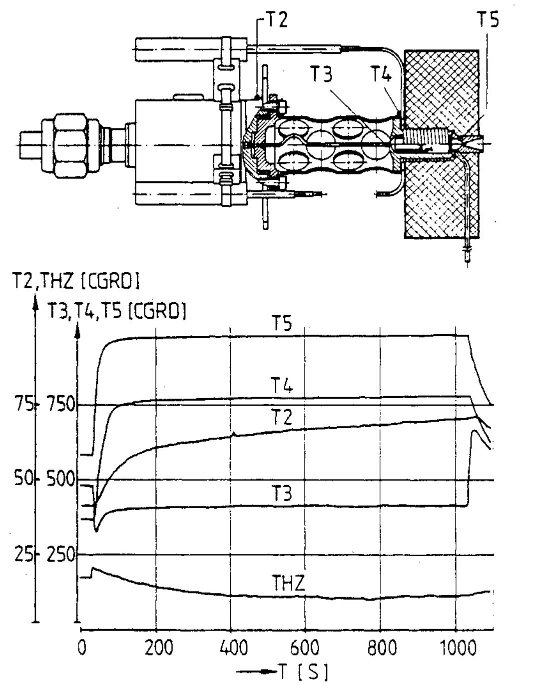

Fig. 5 Decomposer temperature history.

The decomposer life test consisted of 2690 cycles of the 7 min on/3 min off duty cycle. The unit had the exact performance required for the AEHT, as shown in Fig. 4. The maximum thrust amounted to 0.25 N.

The most important result of this life-firing program was the fact that the total pressure drop amounted to less than 4% at 22 bars.

Figure 5 presents the temperature history during one of the firing cycles, the maximum injector temperature during operation reading 420°C. For future AEHT operations, the decomposer heaters will be switched off after the activation of the heat exchanger; this mode of operation has been successfully proven during this test sequence, as well as at all inlet pressures between 22 and 5.5 bars.

Before leaving the decomposer, some comments should be made on the decomposer heaters. After severe problems with the conventional cartridge heaters, which had been designed for the higher power consumption of 20 W, a completely different heater concept was selected. Sheath heaters with the required characteristics were subjected to an extensive program of qualification testing.

Two heaters—one prime and one backup—were assembled to a dummy decomposition chamber. The operating heater was powered constantly and a facility heater inside the decomposition chamber powered in order that the whole assembly could be quickly heated up to 1050°C. Kept in a vacuum of 10^{-4} Torr, the heater was cycled a total of 600 times between 550 and 1050°C, operating a total of more than 750 h at about 1030°C and 13 h even at 1200°C. The number of cycles and the total heating duration by far exceeded the requirements of a 7-yr thruster life.

AEHT Design and Development

As already indicated earlier, the requirements of Table 1, especially the environmental requirements and the off-modulation capability, implies a rugged thruster design. Thus a concept was sought that did not require highly sophisticated and probably vulnerable heaters. The design presented in Fig. 6, in which the heat exchanger itself is used as the heater, was finally adopted. This initial AEHT version consisted of a coiled thin-walled molybdenum/rhenium tube sufficiently long enough to achieve the required resistance. The gas is heated while flowing through the tube on its way to the nozzle. A preliminary test setup was used to generate data relating to warmup characteristics, material behavior, and thermodynamic characteristics.

The unit was tested for about 16,000 s with input power varying between 200 and 550 W. Measurements included decomposer chamber pressure, thrust, and the temperature distribution.

The test results were used to verify the analytical models that had been established earlier in the program. Ongoing calculations in support of the new design activities finally led to the thruster concept presented in Fig. 7.

The products of decomposition leaving the decomposer are led to the inlet of the heat exchanger tube. The heat exchanger tube configuration was redesigned, compared to the first version, to produce an axially symmetric design of thruster. This concept was chosen because of its superior insulation characteristics, which reduce the heat losses. A further improvement would have been possible by reducing the coil diameter of the tube. At the time of the design activities, however, such a tube was not available due to manufacturing problems. The thruster, shown in Fig. 7, was built using materials such as tungsten-zirconium-stabilized molybdenum (TZM), molybdenum tungsten, molybdenum rhenium, and boron nitride as electrical/thermal insulator.

The thruster was subjected to verification testings between 22 and 7.5 bars, delivering 0.25-0.08 N of thrust in vacuum. Figure 8 presents the thruster characteristics that were achieved by applying between 380 and 250 W, resulting in specific impulse values between 2700 and 3100 N·s/kg at the relevant inlet pressures. After about 12 h of AEHT firing, considered as sufficient for the AEHT characterization, the successful 314-h life test of the decomposer was performed (as described above), followed by another AEHT verification test of about 2 h. During these tests the decomposer heaters were switched off to verify a thruster-operating mode being implemented in the future. Due to interface problems with the thruster control assembly, the tests were concluded. Thereafter the thruster was disassembled and sectioned in various areas and metallurgically analyzed.

The tests showed that molybdenum rhenium as heat exchanger material should be replaced by pure rhenium, and the feasibility of using this material was investigated. Subsequent confirmation of the choice enabled further improvement to be incorporated, not only from a material point of view but from a configurational point of view as well.

The bending diameter of the heat exchanger tube could be further decreased, and the design shown in Fig. 9 was

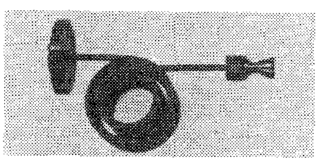

Fig. 6 Heat exchanger design: Version 1.

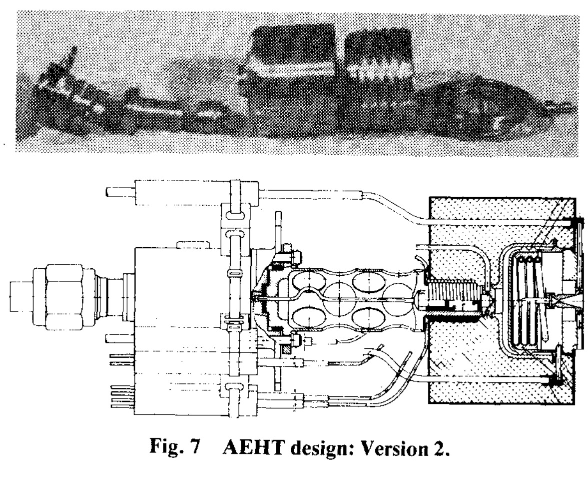

Fig. 7 AEHT design: Version 2.

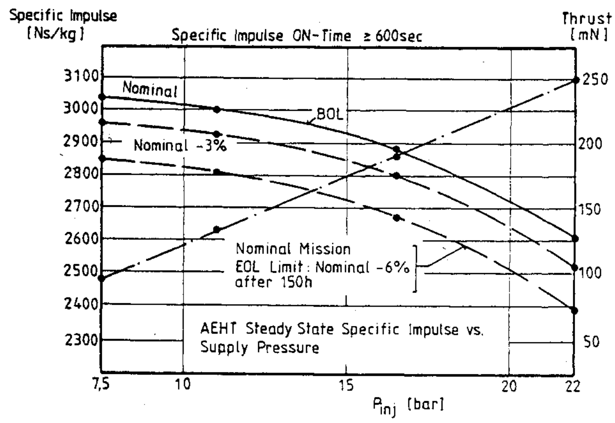

Fig. 8 AEHT performance characteristics.

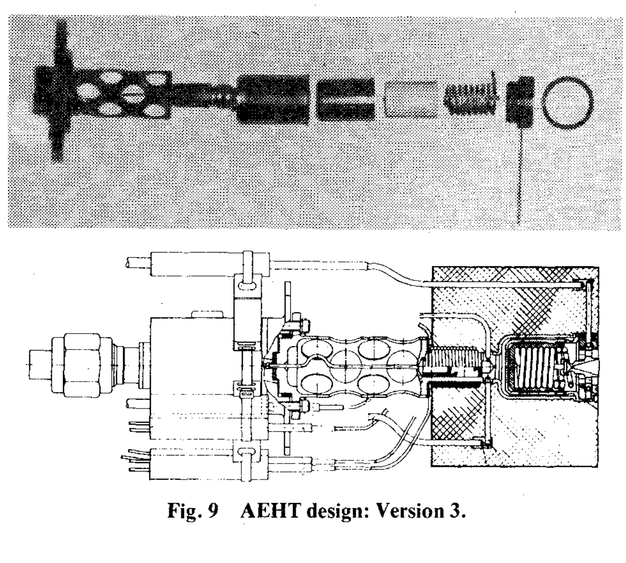

Fig. 9 AEHT design: Version 3.

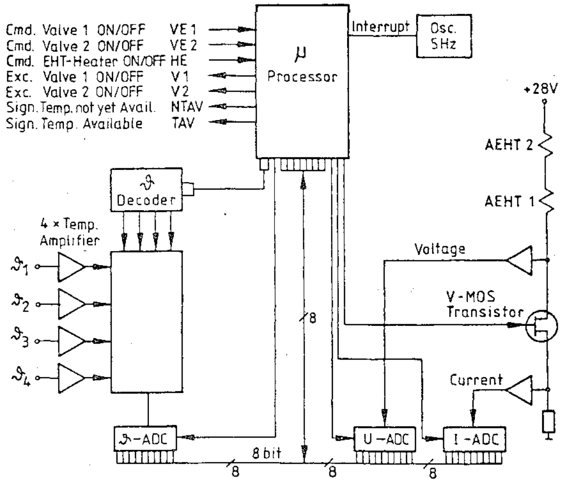

Fig. 10 Thruster control assembly.

achieved. Due to the reduction of the tube coil diameter and some other design improvements, the heat losses could be further decreased.

Tests with this thruster providing at least 200 h of firing are planned for the near future.

Thruster Control Assembly

Parallel to the AEHT itself, a thruster control assembly has been designed, built, and tested together with the thruster. The functions of the thruster control assembly (TCA) are: to provide regulated power; to control the heaters for the decomposer and heat exchanger; and to act as a sequencer for startup and shutdown maneuvers.

The sequence of events to be controlled by the electronic circuitry is as follows:

Startup

1) Activation of decomposer heater;

2) Decomposer temperature monitoring and control (by redundant temperature sensors);

3) Opening of thruster solenoid valve after a defined time delay (by ground command);

4) Activation of heat exchanger with a positive short-time delay; and, simultaneously,

5) Deactivation of decomposer heater.

Shutdown

1) Deactivation of heat exchanger and, simultaneously,

2) Closing of thruster solenoid valve.

The design and concept of the TCA is described briefly in the following.

As two thrusters are always fired simultaneously, the electronic circuitry is designed to control two thrusters simultaneously.

The microprocessor controls the entire electronic circuitry, a block diagram being presented as Fig. 10. The input data are: four temperatures (two sensors per thruster), heat exchanger voltage, and heat exchanger current.

The four temperatures are preamplified and led to a multiplexer controlled by the microprocessor. The temperatures are led to the 8-bit data bus via the analog/digital converters.

The heat exchanger voltage and current are detected at the V-MOS transistor and formatted by amplifiers in order that they can be converted by their individual analog/digital converters and led to the microprocessor data bus as well. By comparison the microprocessor can determine the 1-Ω point of the heater which leads to the switching of the V-MOS transistor.

The external commands VE1/VE2 and HE are given by telecommand and excuted via V1/V2 and H, if all necessary conditions are fulfilled.

TAV and NTAV are signals (telemetry) confirming execution (or nonexecution) of the commands.

Normally such an AEHT with electrothermal decomposer cannot be used after failure of the decomposer heaters. However, this thruster and its control electronics have a useful redundant mode of operation. The TCA can be switched to a manual override position where control of the AEHT heat exchanger is possible without previous activation of the decomposer heaters and the flow control valve. The heat transfer from the heat exchanger to the decomposer is sufficient to achieve starting conditions within a relatively short period. This can be done with no risk of overheating the heat exchanger tube. The only disadvantage is the high-power consumption in this emergency mode for the short heatup period.

Summary

The central objective in the design and development activities described above has been the creation of a rugged and reliable design capable of replacing existing catalytic thrusters for north/south stationkeeping operations.

It is well known that the presented design is not optimal regarding the specific power; however, the thruster can survive the existing Ariane and Shuttle environmental requirements and is capable of operation in an off-modulation mode.